Confronting Naturalness with Higgs Data

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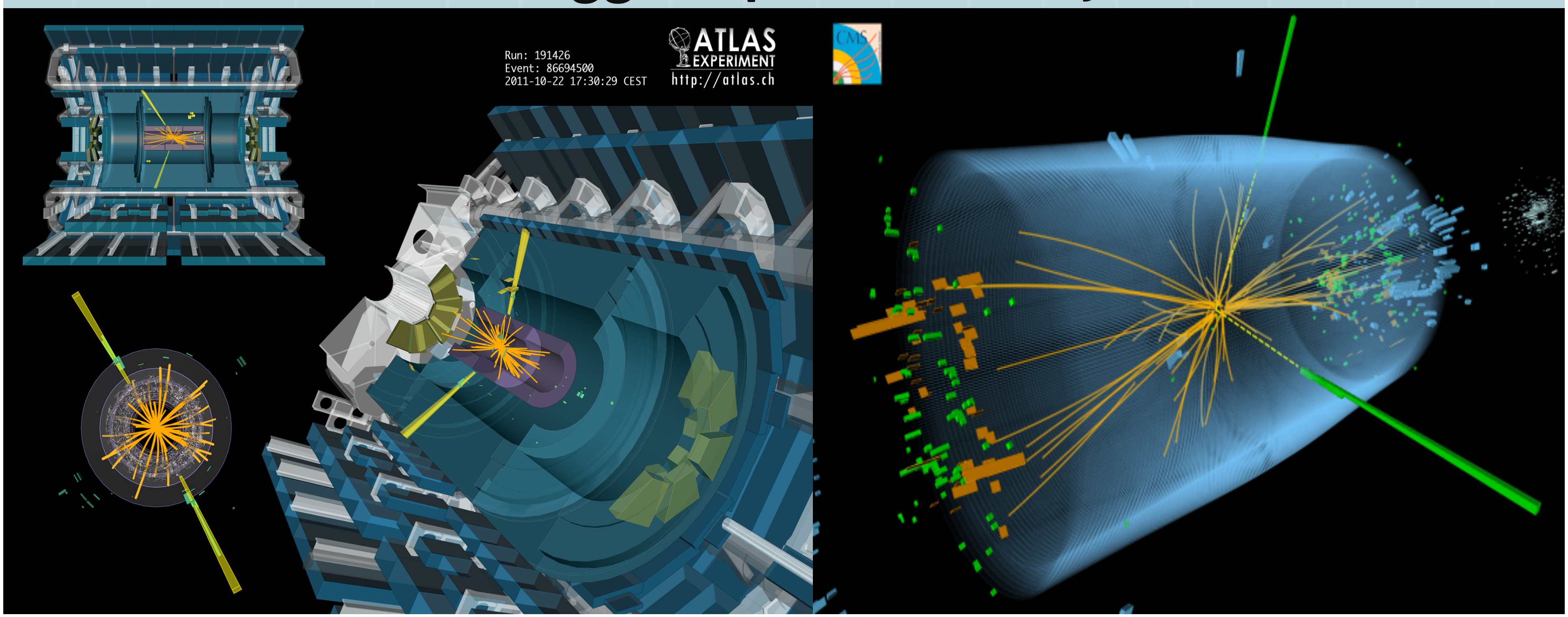
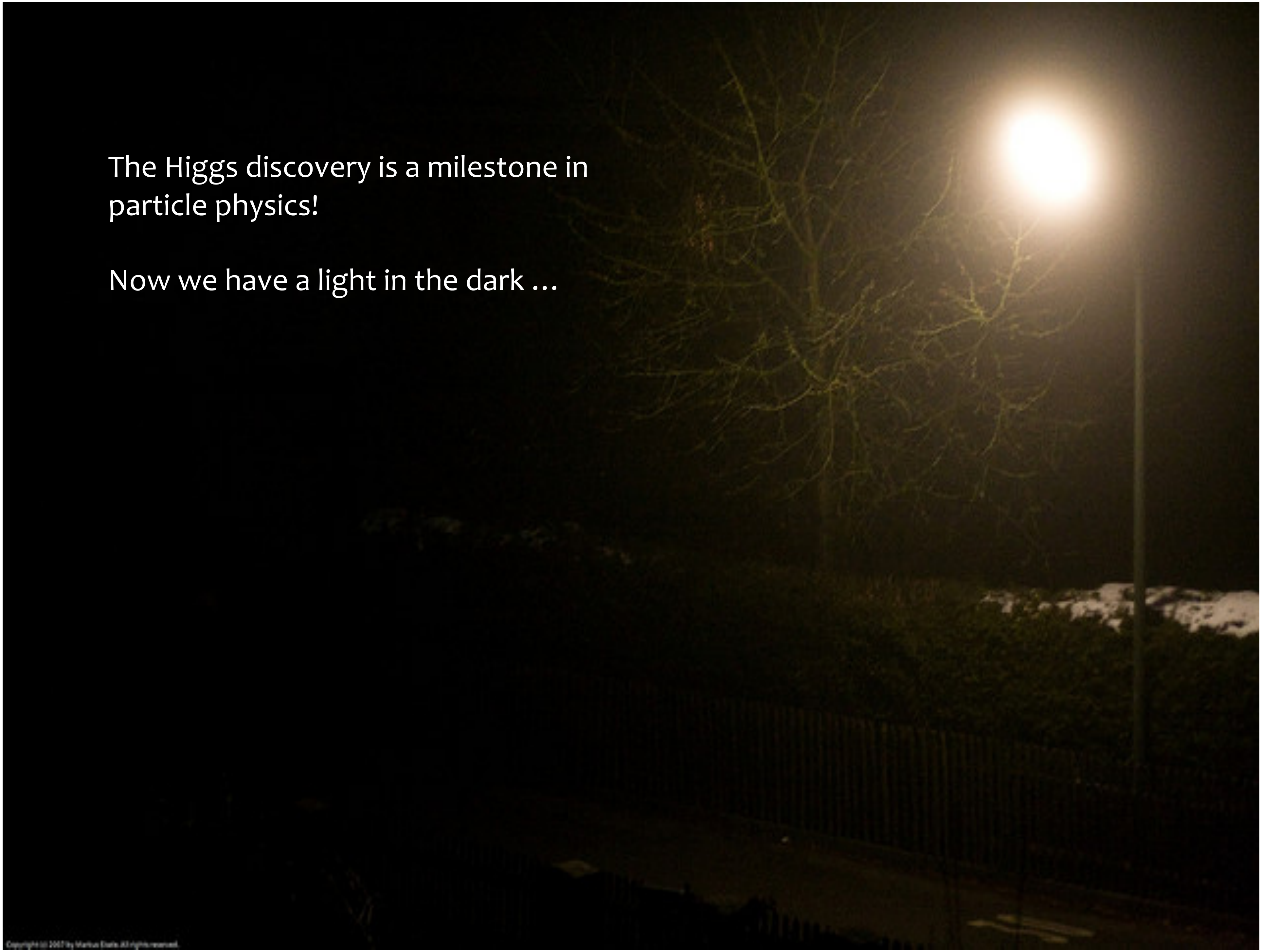
LBNL, 2/20/2014

Higgs Dependence Day




The Higgs discovery is a milestone in particle physics!
Now we have a light in the dark …

The deep question that confronts us at the TeV scale:

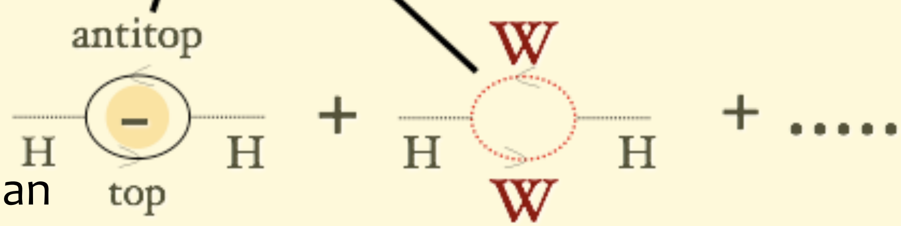
Is Electroweak Symmetry Breaking Natural ?

Hierarchy / naturalness problem

$$V(\phi) = -\frac{1}{2}m_0^2|\phi|^2 + \frac{1}{4}\lambda|\phi|^4$$

$$m_H^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2}\left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2\right)\Lambda^2 \sim m_0^2 - (115\mathrm{GeV})^2\left(\frac{\Lambda}{400\mathrm{GeV}}\right)^2$$

bare mass,
a parameter
In the Lagrangian



Λ= scale up to which the SM is valid

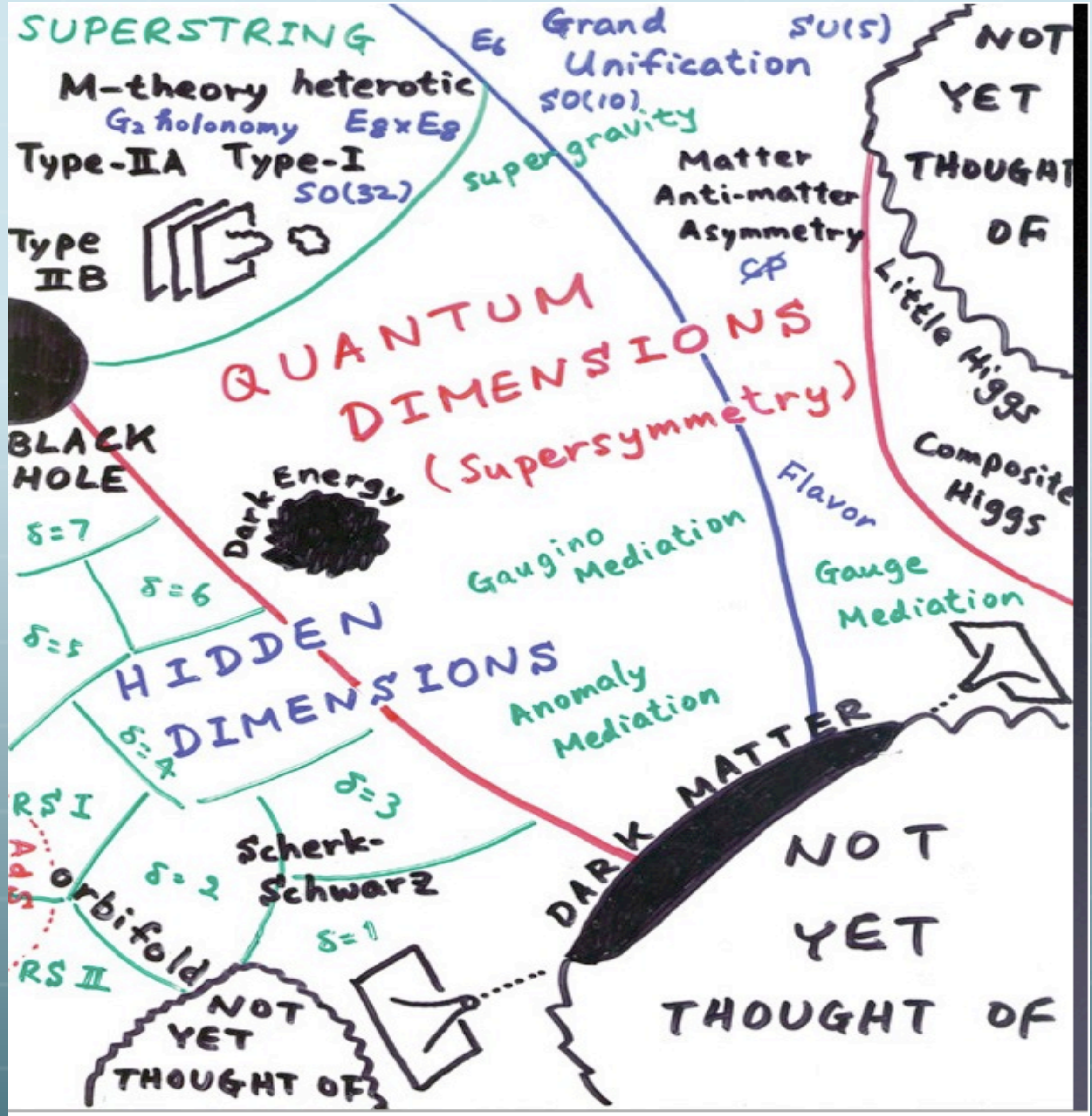
Suppose Λ ~ 10^{16} GeV and physical Higgs mass is 125 GeV,

We need, say, the bare mass m_0^2 = (**373,789,254,211,536** GeV)^2

But suppose the Creator Deity accidentally wrote m_0^2 = (**373,789,254,211,526** GeV)^2

Then the physical Higgs mass is 10^8 GeV!

"Hierarchy/naturalness problem" drives 40 years speculative/creative theory works



Hitoshi Murayama

- Implications of Higgs mass for naturalness
- Natural Higgs is not a SM-like Higgs
- A new look at Higgs constraints on stops in Natural SUSY
- Correlation between Higgs coupling deviations and a new bosonic mass scale

Hints from Higgs Mass

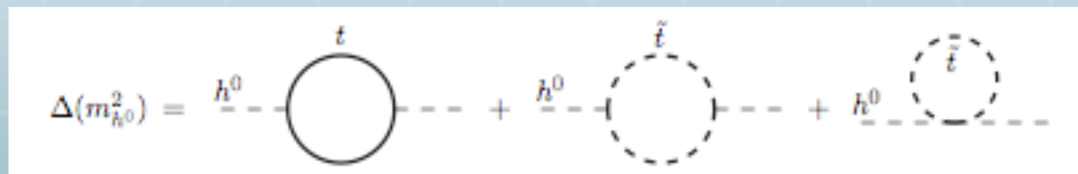
Higgs mass in the minimal supersymmetric standard model

tree level:

$$V = |F|^2 + |D|^2,$$

$$V \supset \frac{1}{8}(g^2 + g'^2)(h_u^{02} + h_d^{02})^2$$

1-loop level:



$$X_t \equiv A_t - \mu \cot \beta$$

Higgs-stop-stop trilinear coupling

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

$$\gtrsim (85\text{GeV})^2$$

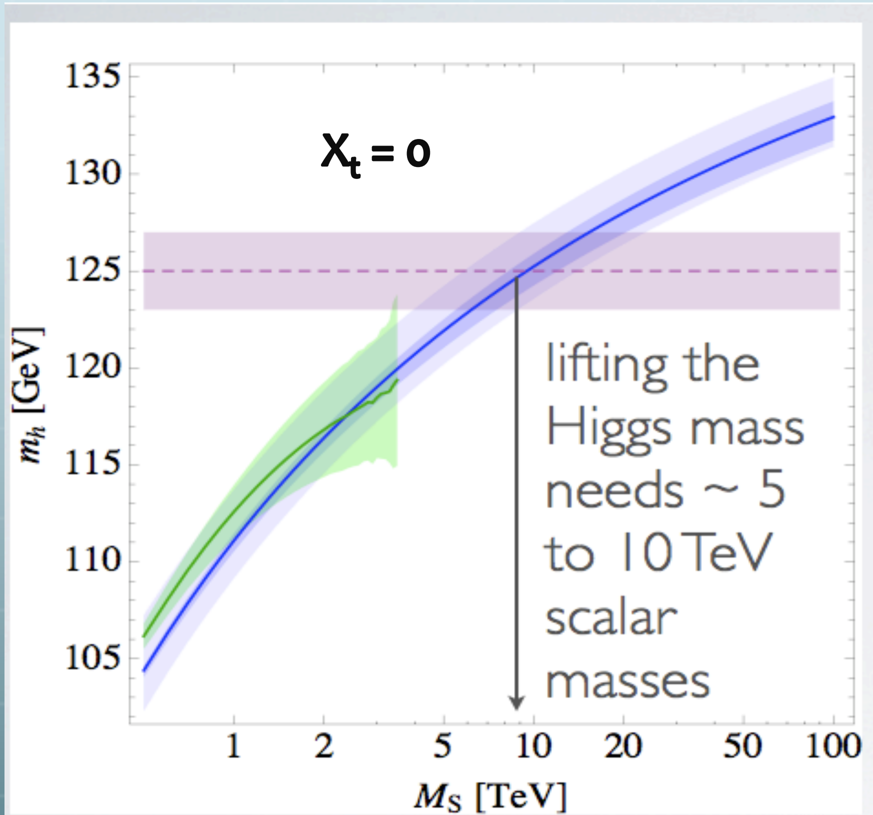
< (90 GeV)²

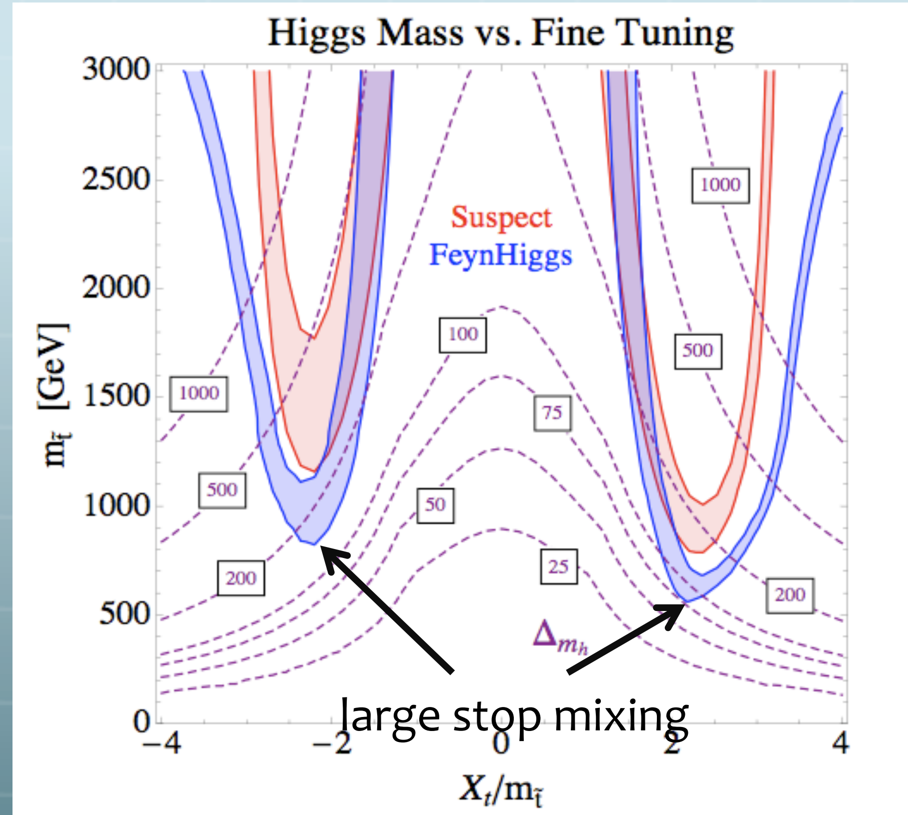
$$M_S \equiv \left(m_{\tilde{t}_1} m_{\tilde{t}_2}\right)^{1/2}$$

Higgs mass in MSSM

$$X_t \equiv A_t - \mu \cot \beta$$

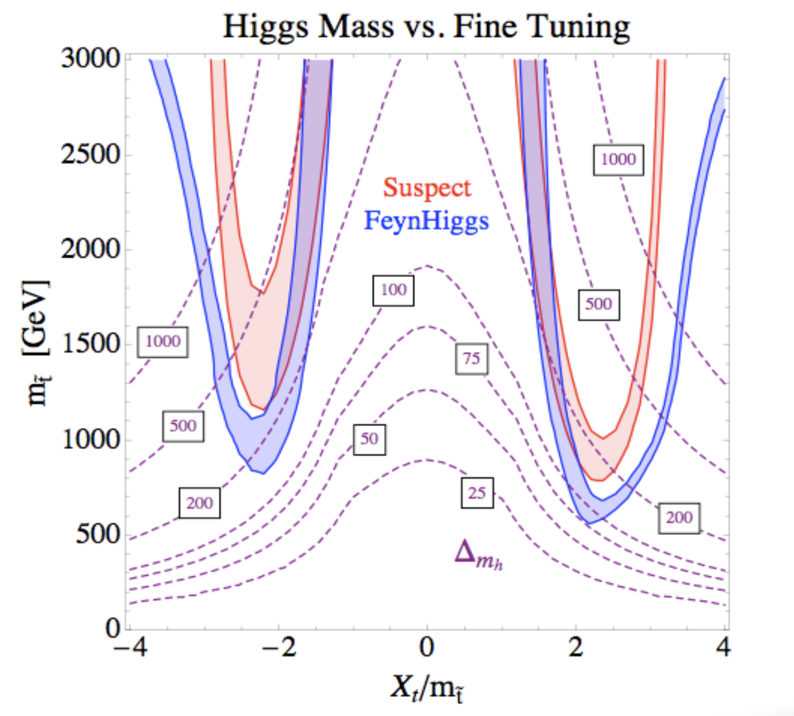
$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right)$$





Draper, Meade, Reece, Shih 2011;

Hall, Pinner, Ruderman 2011;



In MSSM, to get the Higgs mass to be 125 GeV, a large quantum correction must be introduced with multi-TeV SUSY breaking parameters;

the fine-tuning is worse than a few percent.
MSSM is tuned!!

$$|X_t| \gtrsim 1000 \text{ GeV}, \quad M_S \gtrsim 500 \text{ GeV}.$$

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

$$\gtrsim (85\text{GeV})^2$$

Barbieri, Giudice, 1988; Kitano, Nomura 2006

SUSY breaking mediation scale

$$(\Delta_Z^{-1})_{\tilde{t}} = \left|\frac{2\delta m_{H_u}^2}{m_h^2}\right|, \qquad \delta m_{H_u}^2|_{stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u3}^2 + A_t^2\right) \log\left(\frac{\Lambda}{\text{TeV}}\right).$$

- To keep SUSY natural, one must go beyond MSSM and add new tree-level interactions to raise the Higgs mass.
- Non-decoupling D-term models Batra, Delgado, Kaplan, Tait 2003

  Higgs doublets charged under new gauge group beyond the SM
- F-term models

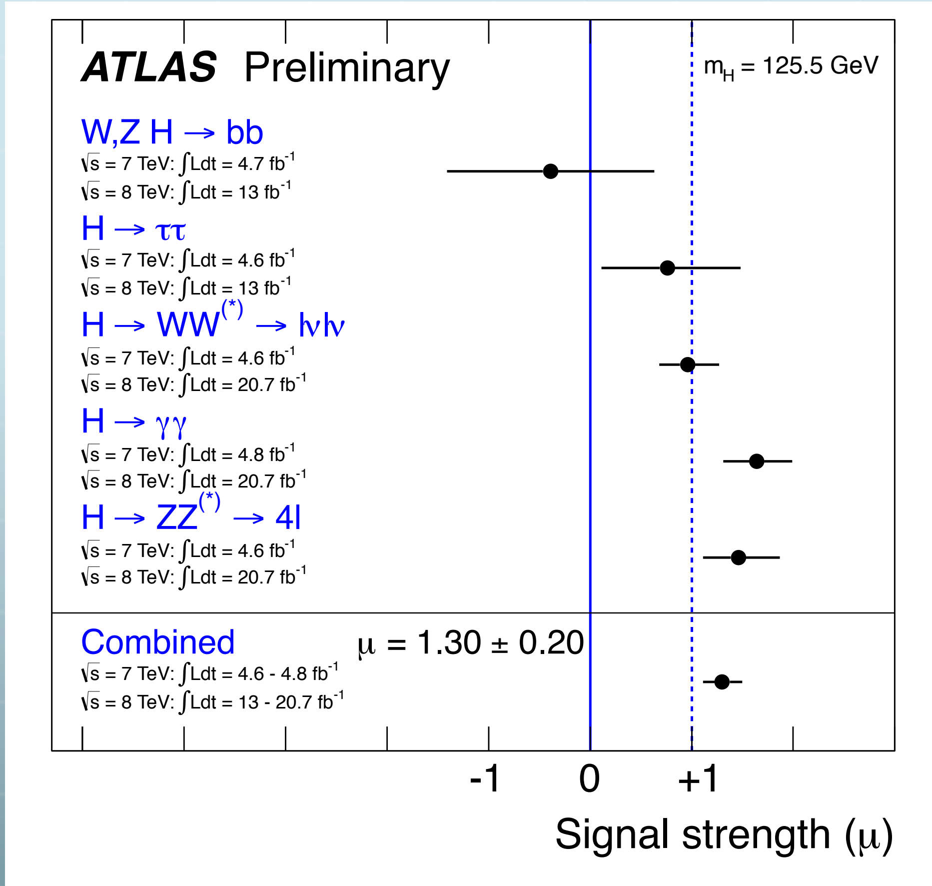
$$W = \lambda S H_u H_d + f(S)$$

NMSSM Espinosa,Quiros 1992

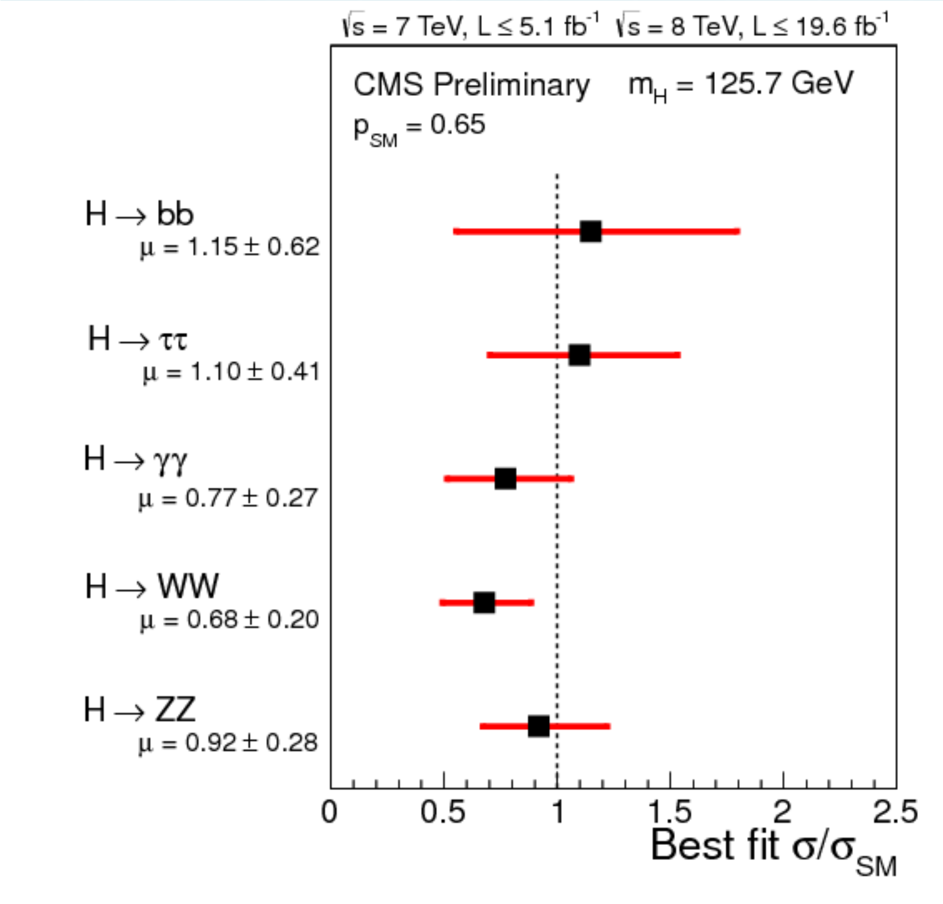
Dirac NMSSM Lu, Murayama, Ruderman, Tobioka 2013

λSUSY Hall, Pinner, Ruderman 2011

Higgs Couplings in Natural SUSY



Channel	μ	$\zeta_i^{(G,V,T)}$ (%)
$b\bar{b}$	$0.2^{+0.7}_{-0.6}$	$(0,100,0)$
$\tau\bar{\tau}$ (boosted)	$1.2^{+0.8}_{-0.6}$	$(66,34,0)$
$\tau\bar{\tau}$ (VBF)	$1.6^{+0.6}_{-0.5}$	$(10,90,0)$
$WW(0/1j)$	$0.82^{+0.33}_{-0.32}$	$(98,2,0)$
$WW(2j)$	$1.4^{+0.7}_{-0.6}$	$(19,81,0)$
ZZ (other)	$1.45^{+0.43}_{-0.36}$	$(90.4,9.6,0)$
ZZ (VBF + VH)	$1.2^{+1.6}_{-0.9}$	$(37.0,63.0,0)$
$\gamma\gamma$ (low p_T)	$1.6^{+0.5}_{-0.4}$	$(91.1,8.6,0.3)$
$\gamma\gamma$ (high p_T)	$1.7^{+0.7}_{-0.6}$	$(78.6,19.9,1.4)$
$\gamma\gamma$ $(2j)$	$1.9^{+0.8}_{-0.6}$	$(32.3,67.7,0)$
$\gamma\gamma$ (VH)	$1.3^{+1.2}_{-1.1}$	$(22.4,68.1,9.5)$



Channel	μ	$\zeta_i^{(\mathrm{G,V,T})}$ (%)
$b\bar{b}$ (VBF)	1.0 ± 0.5	$(0, 100, 0)$
$\tau\bar{\tau}(0j)$	0.34 ± 1.09	$(98.1, 1.9, 0)$
$\tau\bar{\tau}(1j)$	1.07 ± 0.46	$(77.3, 22.7, 0)$
$\tau\bar{\tau}(2j)$	0.94 ± 0.41	$(19.0, 81.0, 0)$
$\tau\bar{\tau}(VH)$	-0.33 ± 1.02	$(0, 100, 0)$
$WW(0/1j)$	$0.74^{+0.22}_{-0.2}$	$(95.7, 4.3, 0)$
$WW(2j;\ \mathrm{VBF})$	$0.6^{+0.57}_{-0.46}$	$(22.3, 77.7, 0)$
$WW(3\ell 3\nu)$	$0.56^{+1.27}_{-0.95}$	$(0, 100, 0)$
$ZZ(0/1j)$	$0.83^{+0.31}_{-0.25}$	$(92.8, 7.2, 0)$
$ZZ(2j)$	$1.45^{+0.89}_{-0.62}$	$(54.8, 42.5, 2.7)$
$\gamma\gamma$ (untagged 0; 8 TeV)	$2.12^{+0.92}_{-0.78}$	$(72.9, 24.6, 2.6)$
$\gamma\gamma$ (untagged 3; 8 TeV)	$-0.81^{+0.85}_{-0.42}$	$(92.5, 7.2, 0.2)$
$\gamma\gamma$ (dijet; 8 TeV)	$4.13^{+2.33}_{-1.76}$	$(26.8, 73.1, 0.0)$
$\gamma\gamma$ (dijet loose; 8 TeV)	$0.75^{+1.06}_{-0.99}$	$(46.8, 52.8, 0.5)$
$\gamma\gamma$ (dijet tight; 8 TeV)	$0.22^{+0.71}_{-0.57}$	$(20.7, 79.2, 0.1)$
$\gamma\gamma$ (MET; 8 TeV)	$1.84^{+2.65}_{-2.26}$	$(0.0, 79.3, 20.8)$

Higgs couplings

- Radiative effect: hgg, hγγ couplings

  Low energy Higgs theorem: hgg, hγγ couplings are related to beta function coefficients Ellis, Gaillard, Nanopoulos 1976; Shifman, Vainshtein, Voloshin, Zakharov 1979

Higgs couplings

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Kinetic term $$\mathcal{L} = -\frac{1}{4g^2} G^a_{\mu\nu} G^{a\mu\nu}$$

Run the gauge coupling from Λ to μ with an intermediate scale M, at which the beta function coef. changes from b to b+Δb

$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} + \frac{b}{8\pi^2} \log \frac{\Lambda}{\mu} + \frac{\Delta b}{8\pi^2} \log \frac{\Lambda}{M}$$

- **Suppose the intermediate mass threshold M is a function of the Higgs field M=M(h(x)) , one can extract from the gauge kinetic term the Higgs coupling**

$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} + \frac{b}{8\pi^2}\log\frac{\Lambda}{\mu} + \frac{\Delta b}{8\pi^2}\log\frac{\Lambda}{M}$$

M(h)|$_{<h>=v}$

$$\frac{\Delta b}{32\pi^2}\frac{h}{v}G^a_{\mu\nu}G^{a\mu\nu}\frac{\partial \log M(v)}{\partial \log v}$$

Any heavy matter with mass proportional to the Higgs VEV contributes with the same sign, whether it is a fermion or a scalar

Radiative effect in SUSY: stops

three SUSY breaking parameters

$$m_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + \Delta_{\tilde{u}_L} & m_t X_t \\ m_t X_t^* & m_{U_3}^2 + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix}$$

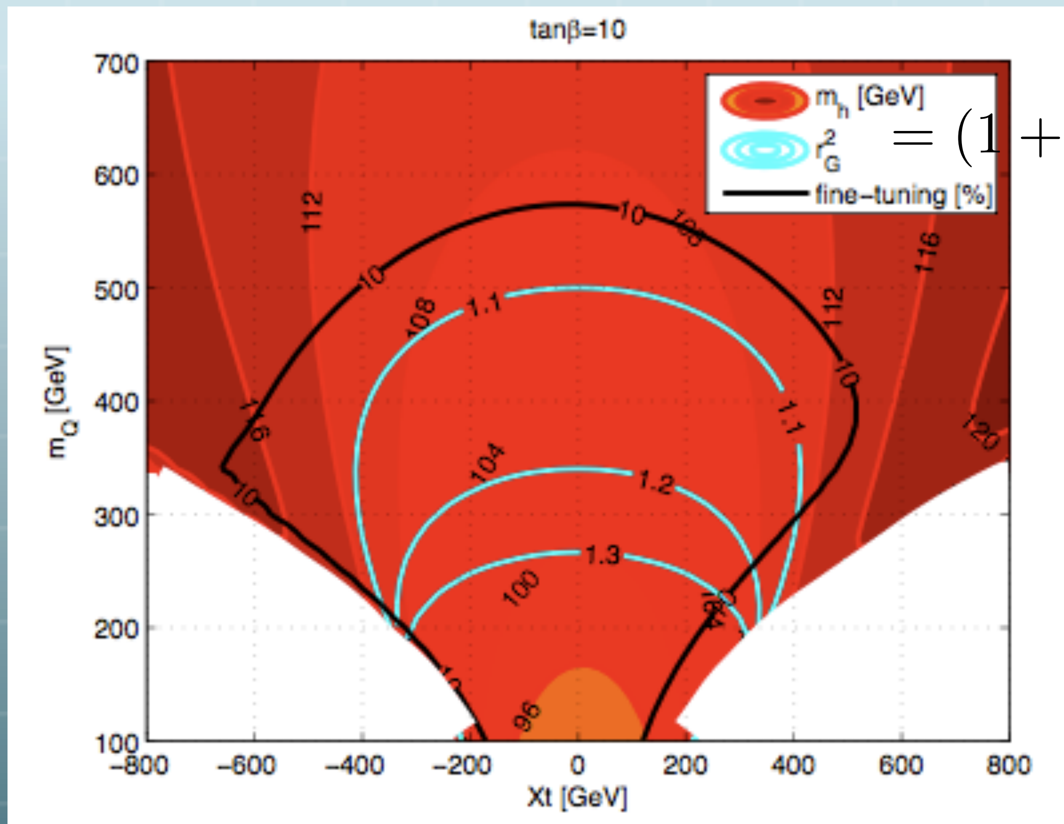
$$r_G^{\tilde{t}} = \frac{c_{hgg}^{\tilde{t}}}{c_{hgg}^{\rm SM}} \approx \frac{1}{4} \frac{\partial \log \mathrm{Det}\, m_{\tilde{t}}^2}{\partial \log v}$$

$$= \frac{1}{4}\left(\frac{m_t^2}{\boxed{m_{\tilde{t}_1}^2}} + \frac{m_t^2}{\boxed{m_{\tilde{t}_2}^2}} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} \right), \quad \text{stop contribution to } hgg \text{ coupling}$$

Physical stop masses squared

Natural Higgs is not a SM-like Higgs!

$$r_G^{\tilde{t}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right), \quad \text{stop contribution,}$$



$$= (1 + r_G^{\tilde{t}})^2$$

Blum, D'Agnolo, JF , 2012

Since there are three parameters in the stop mass squared matrix, when plotting constraints from Higgs coupling on the stop sector, usually people made a variety of choices, e.g., fix X_t or the mixing angle and plot in the physical mass plane.

What I am going to present next is a new way of visualizing the constraints. It is a more effective way to extract the bottom line:
what do measured Higgs properties tell us about allowed stop masses?

JF and Reece 2014

$$\begin{pmatrix} m_{Q_3}^2 + m_t^2 + \Delta_{\tilde{u}_L} & m_t X_t \\ m_t X_t^* & m_{U_3}^2 + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix}$$

diagonal mass splitting

off-diagonal splitting

$$\left| m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2 \right| = \sqrt{(m_{Q_3}^2 + \Delta_{\tilde{u}_L} - m_{U_3}^2 - \Delta_{\tilde{u}_R})^2 + 4 m_t^2 X_t^2},$$

For fixed physical stop masses,

$$\boxed{\left| X_t^{\max} \right| = \frac{\left| m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2 \right|}{2 m_t}},$$

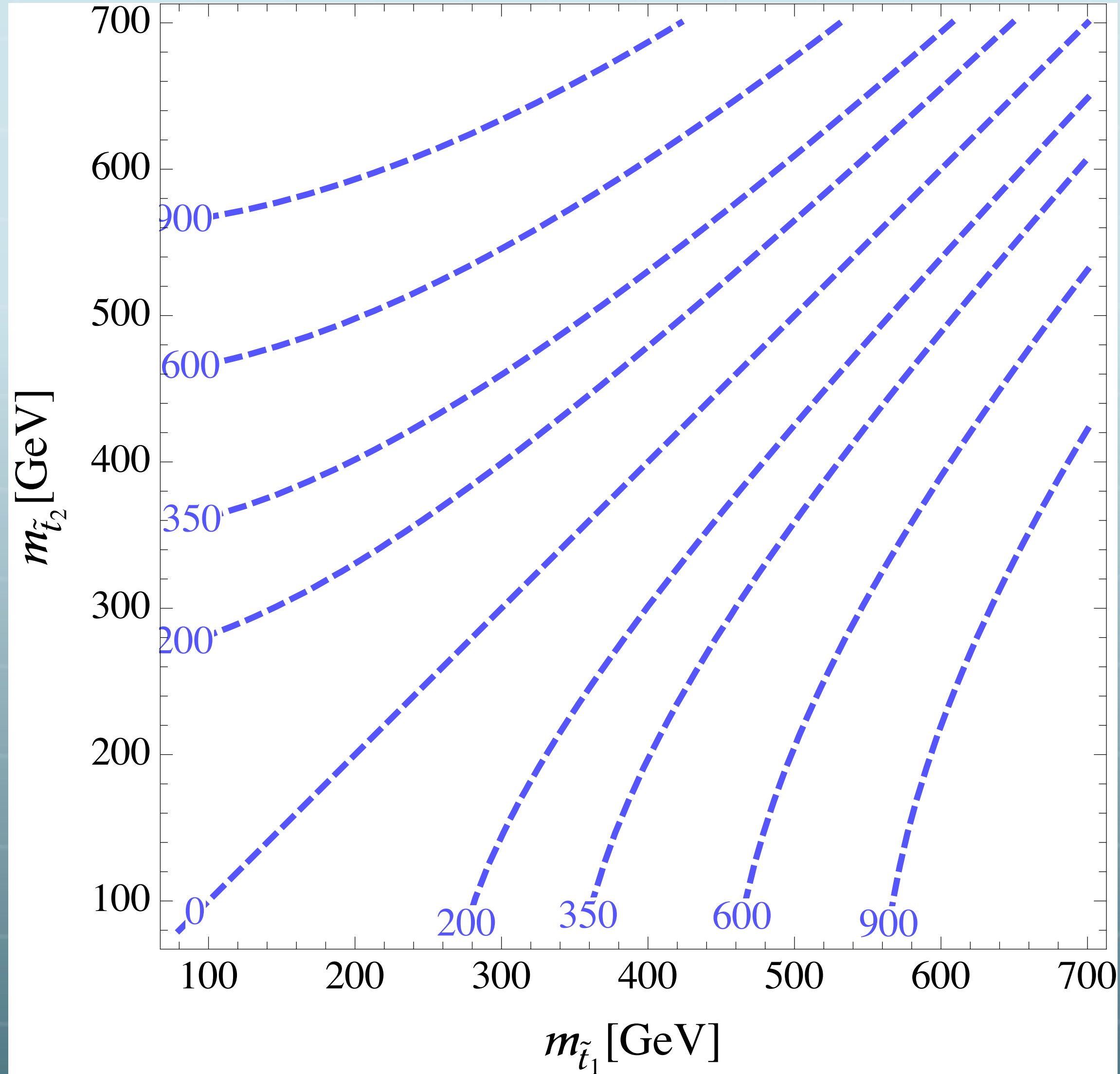
$$r_G^{\tilde{t}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right), \quad \text{stop contribution},$$

Without mixing, light stops could give a considerable positive contribution to hgg coupling.
If it exceeds the upper bound allowed by data, there must be a cancelation between the first two positive terms and the last negative term:

$$\boxed{\left|X_t^{\min}\right| = \frac{\sqrt{m_t^2(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2) - 4\left(r_G^{\tilde{t}}\right)^{\text{fit;max}} m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}}{m_t}}$$

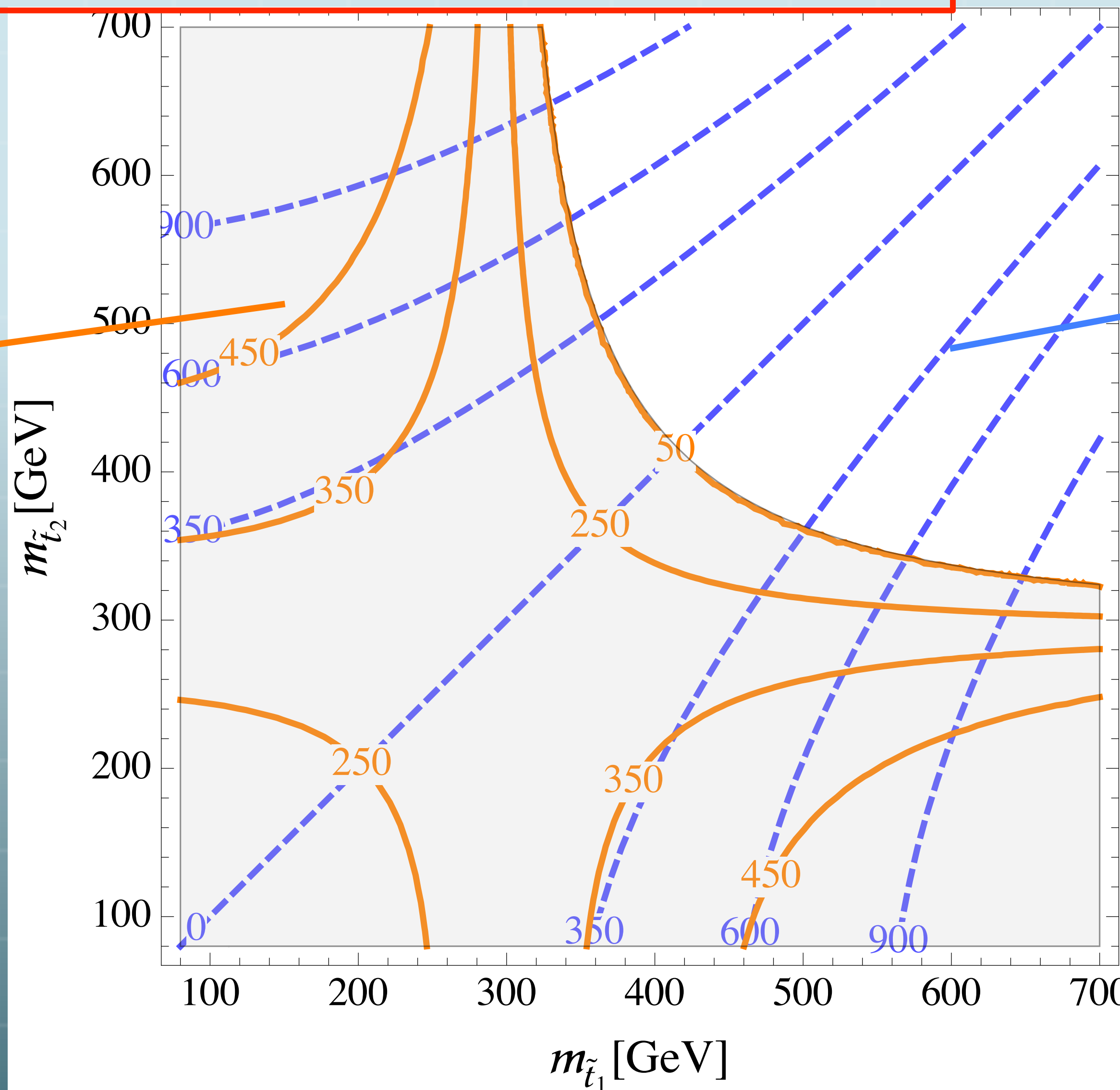
When $|X_t^{\min}| > |X_t^{\max}|$ at a point with fixed physical stop masses, the point is excluded by Higgs data!

$$\left|X_t^{\max}\right| = \frac{\left|m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2\right|}{2m_t},$$



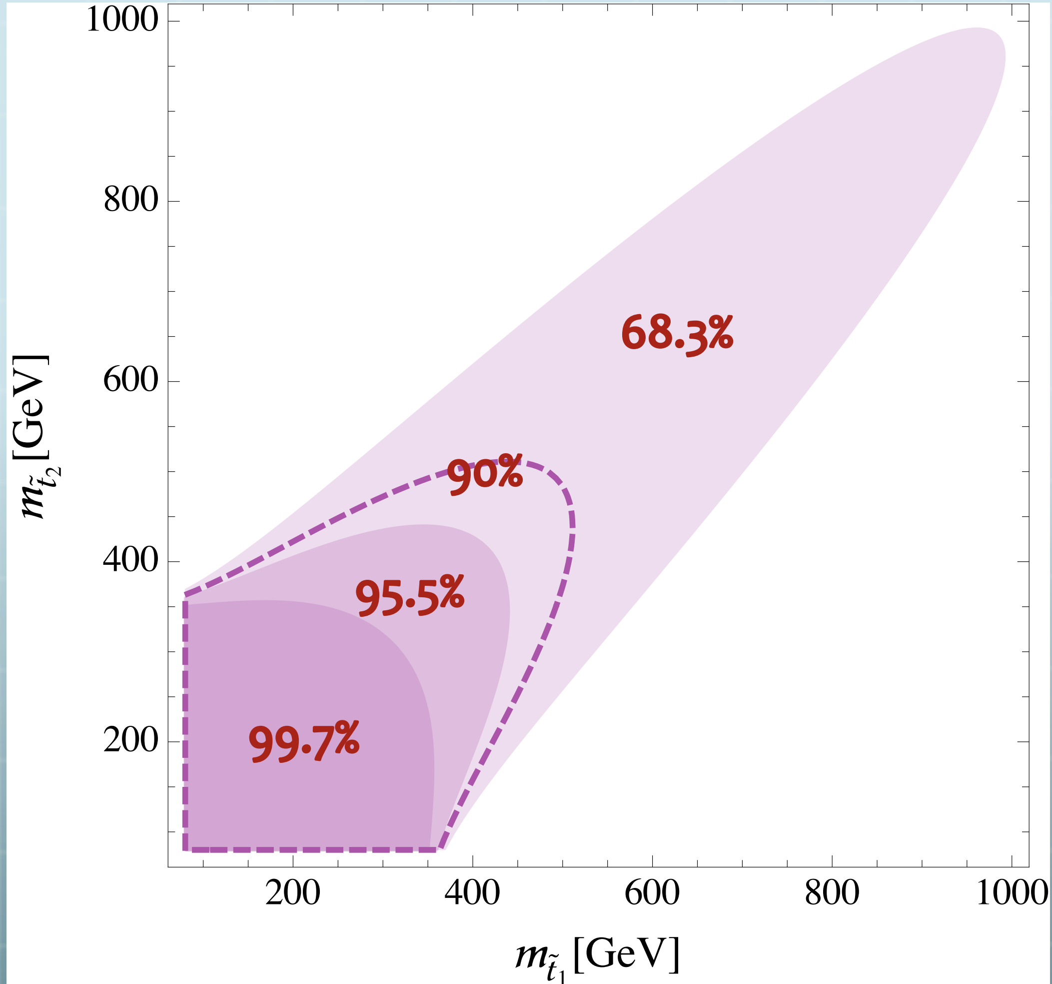
$$\left|X_t^{\min}\right| = \frac{\sqrt{m_t^2(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2) - 4\left(r_G^{\tilde{t}}\right)^{\text{fit;max}} m_{\tilde{t}_1}^2\, m_{\tilde{t}_2}^2}}{m_t}$$

$|X_t^{min}|$



$|X_t^{max}|$

Assume only stops modify Higgs coupling (assuming Yukawa couplings are not modified)



Fine-tuning associated with Higgs coupling:

$$\left(\Delta_G^{-1}\right)_{\tilde{t}} = \left|\sum_i \left(\frac{\partial \log r_G^{\tilde{t}}}{\partial \log p_i}\right)^2\right|^{1/2} \qquad p = (m_{Q_3}^2, m_{U_3}^2, X_t).$$

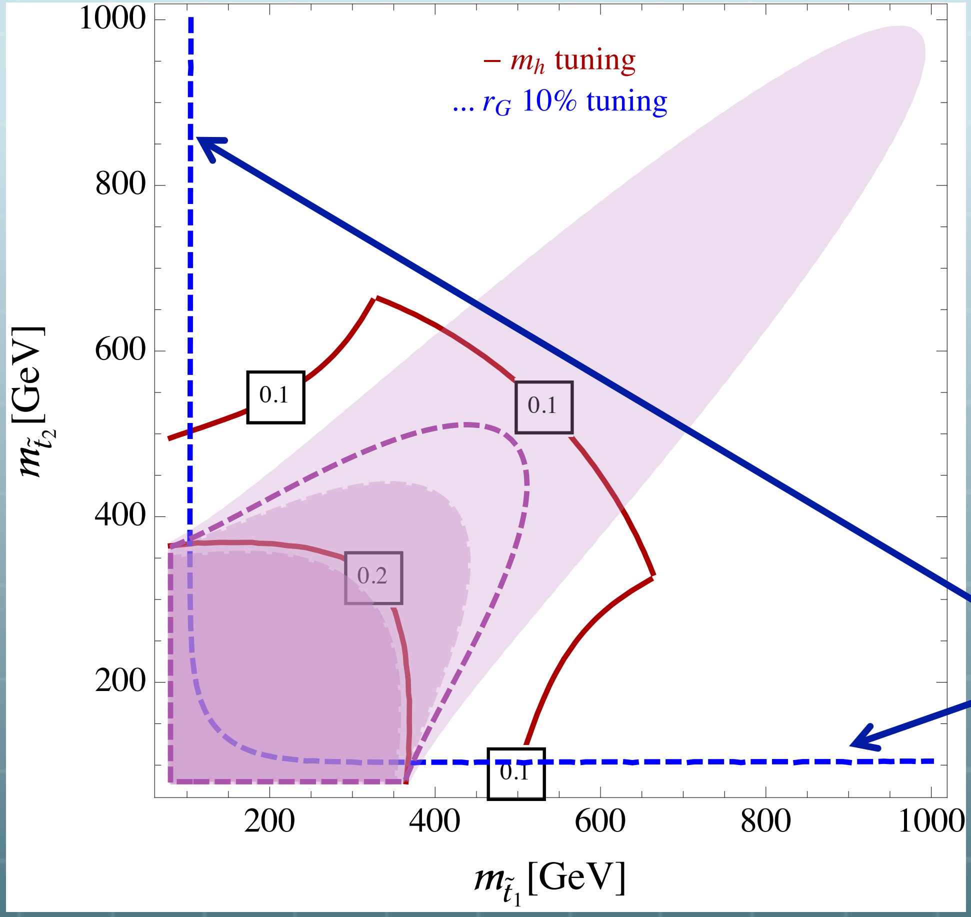
More intuitively,

$$r_G^{\tilde{t}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right), \quad \text{stop contribution},$$

$$\left(\Delta_G^{-1}\right)_{\tilde{t}} \sim \left|\frac{\frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}}{\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}}\right| = \left|\frac{X_t^2}{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - X_t^2}\right|.$$

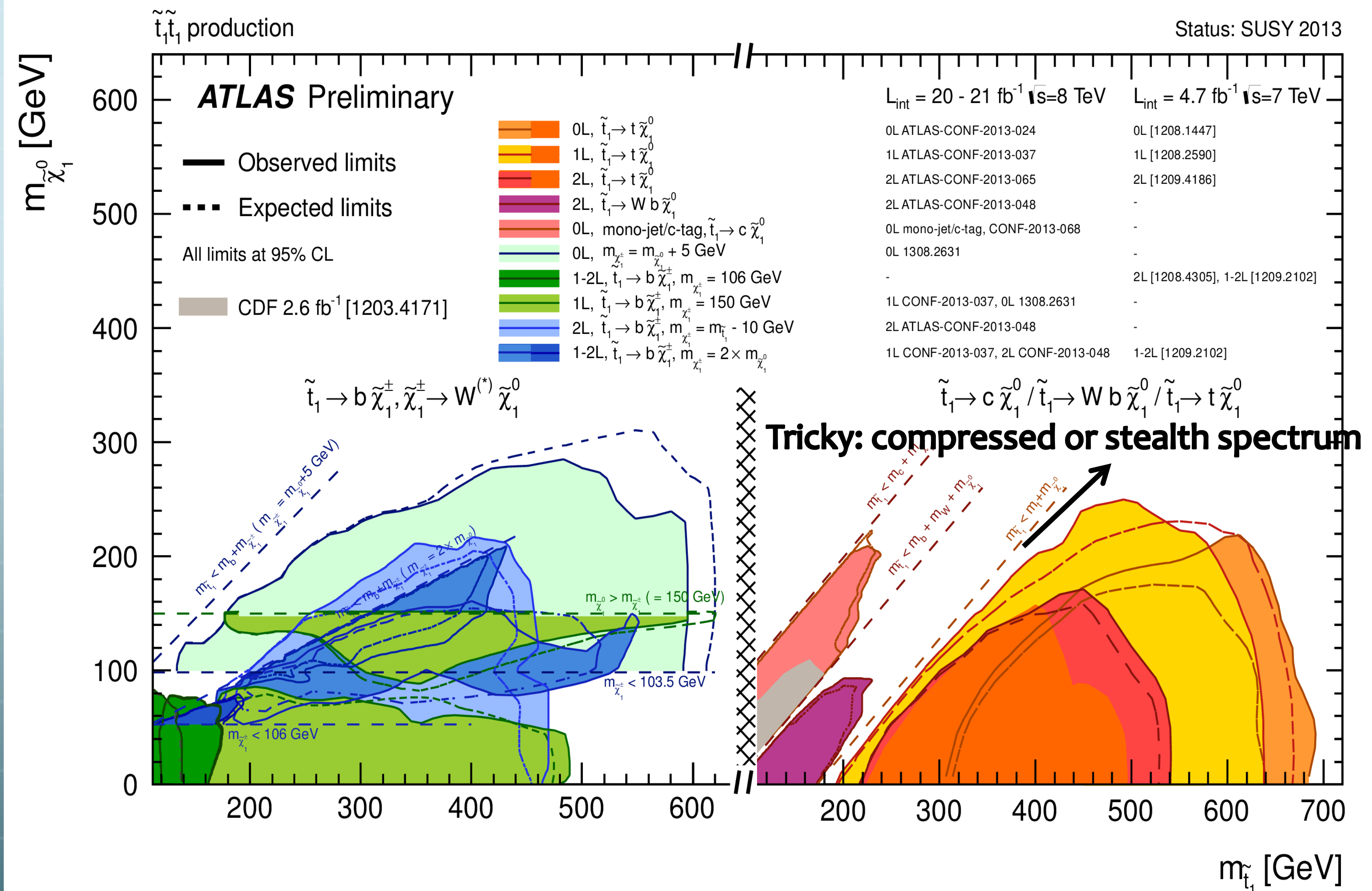
Fine-tuning associated with Higgs coupling:

$$\left(\Delta_G^{-1}\right)_{\tilde{t}} = \left|\sum_i \left(\frac{\partial \log r_G^{\tilde{t}}}{\partial \log p_i}\right)^2\right|^{1/2} \qquad \left(\Delta_G^{-1}\right)_{\tilde{t}} \sim \left|\frac{X_t^2}{m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2 - X_t^2}\right|$$



10 % fine – tuning excludes even one stop below 100 GeV

Collider Constraints on Stops



Summary:

Higgs coupling measurements rules out that both stops with mass below 400 GeV in the case when stops are the only contribution to the Higgs coupling modification.

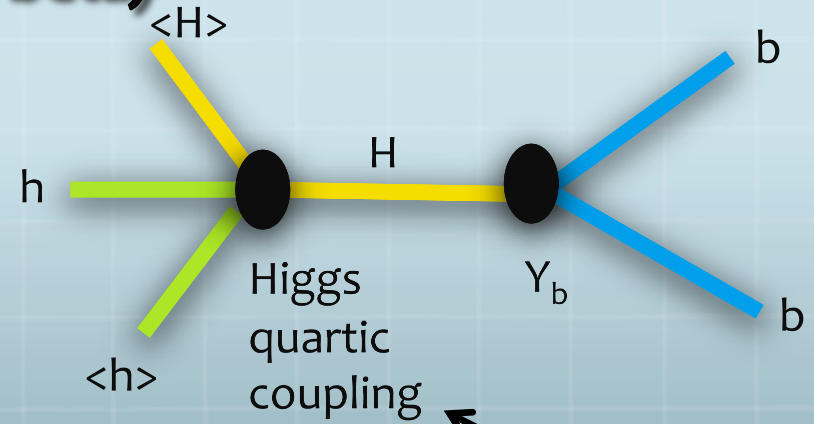
These constraints apply no matter how stops decay and suggest a minimum electroweak fine-tuning of between a factor of 5 and 10.

There could be another source of Higgs coupling modification in SUSY from Higgs mixings in the Higgs sector. The Higgs mixings could modify the Higgs couplings to SM massive particles, in particular, bottom Yukawa.

Could the constraint on the stop sector be relaxed in the presence of multiple variations of Higgs couplings?

- **Higgs mixing effects:**

Eg: type II 2HDM (where the second Higgs is heavy and large tan beta)



$$r_b \equiv \frac{v c^{\mathrm{SUSY}}_{hb\bar{b}}}{m_b} \sim 1 - \frac{\lambda v^2}{m_H^2}$$ **Heavy Higgs mass**

$$m_H^2 \to \infty \quad r_b \to 1$$

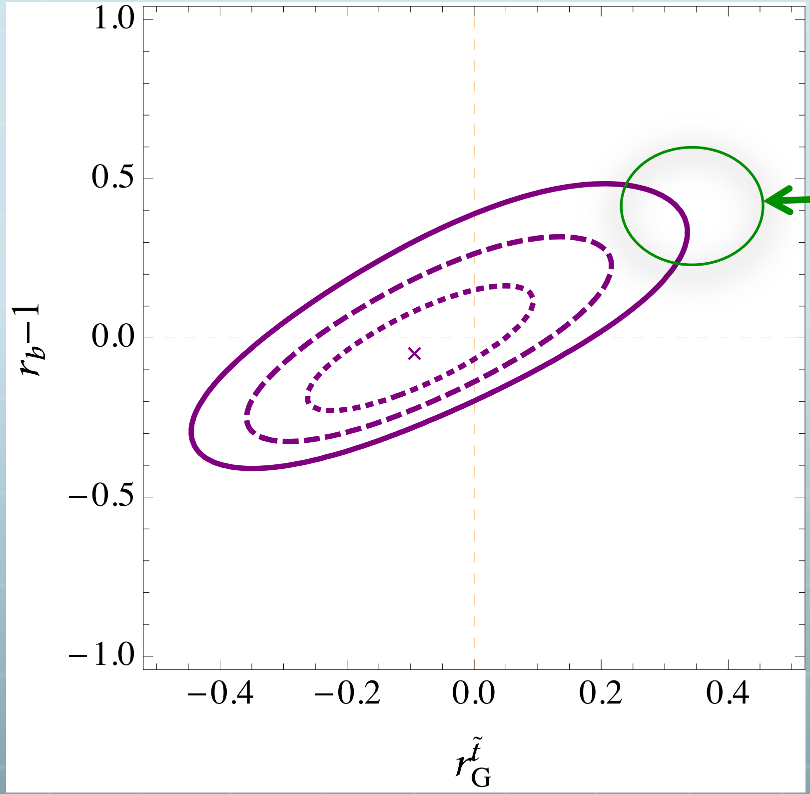
Include Higgs mixing effect at large tan β or equivalently include modification to bottom Yukawa

$$r_b = \frac{v c_{hb\bar{b}}}{m_b}, \quad r_t = \frac{v c_{ht\bar{t}}}{m_t}, \quad r_V = \frac{v c_{hVV}}{2m_V^2},$$

$$r_t = \sqrt{1 - \frac{r_b^2 - 1}{\tan^2\beta}}, \quad r_V = \frac{\tan\beta}{1+\tan^2\beta}\left(\frac{r_b}{\tan\beta} + \sqrt{1+\tan^2\beta - r_b^2}\right)$$

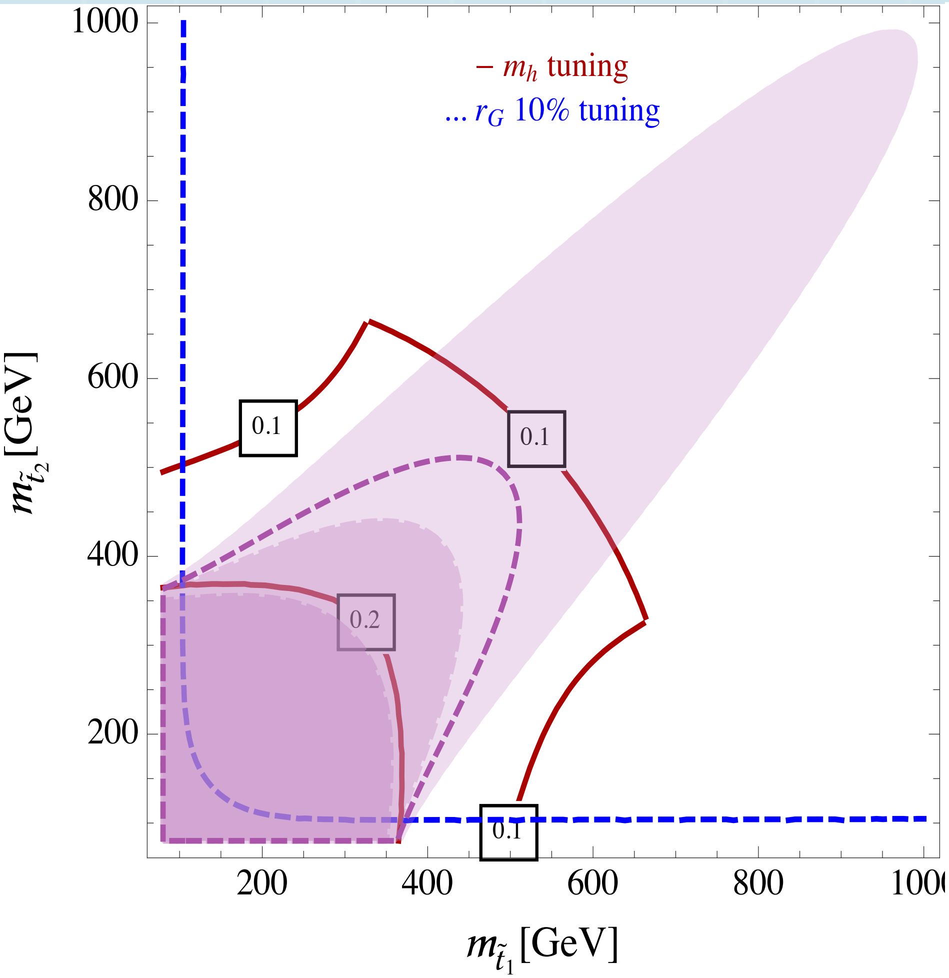
$$\text{At large} \tan\beta, r_t \approx r_V \approx 1$$

Global fit with two parameters

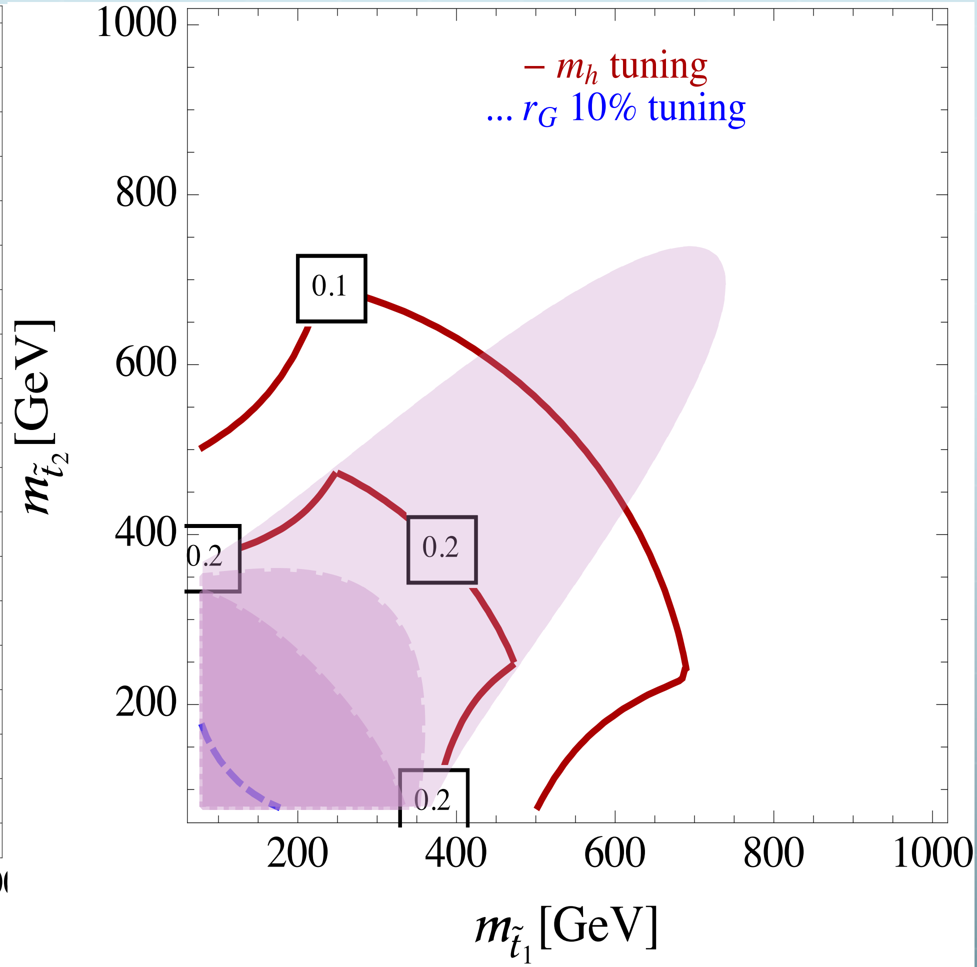


When bottom Yukawa is enhanced, the reduction in branching ratios of most channels compensate the increase in gluon fusion rate due to an enhanced Higgs digluon rate

Vary only Higgs digluon coupling



Vary Higgs digluon coupling and bottom Yukawa



With an enhanced bottom Yukawa, constraints could be relaxed a bit.

Now estimate the size of the deviation in bottom Yukawa in a concrete model, e.g, D-term model with new gauge interactions

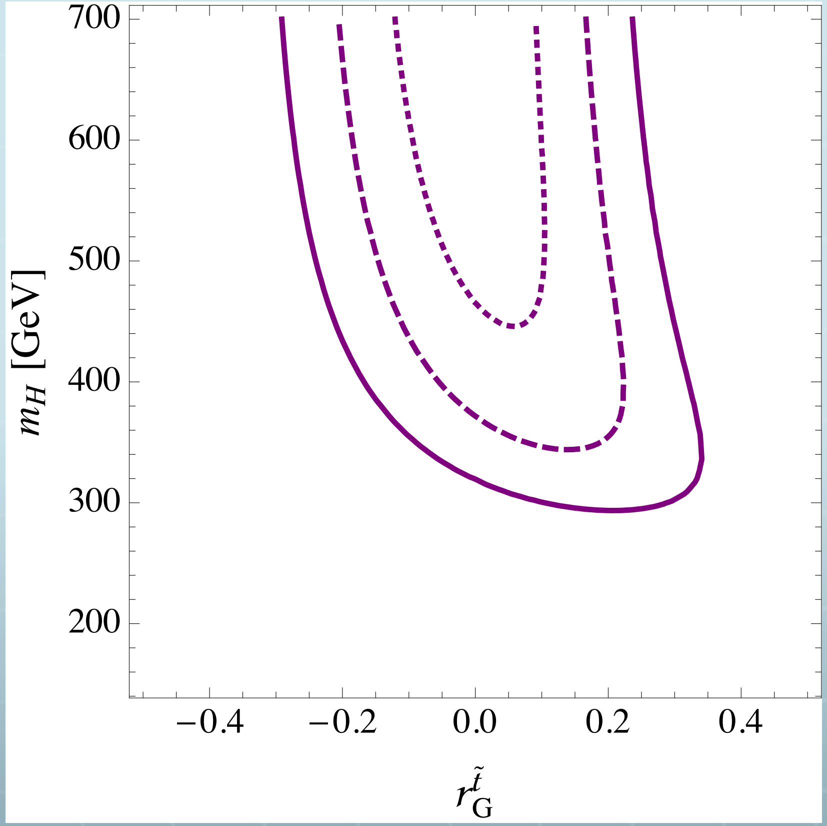
$$V \supset \frac{g^2(1+\Delta) + g'^2(1+\Delta')}{8}\left(\left|h_u^0\right|^2 - \left|h_d^0\right|^2\right)^2$$

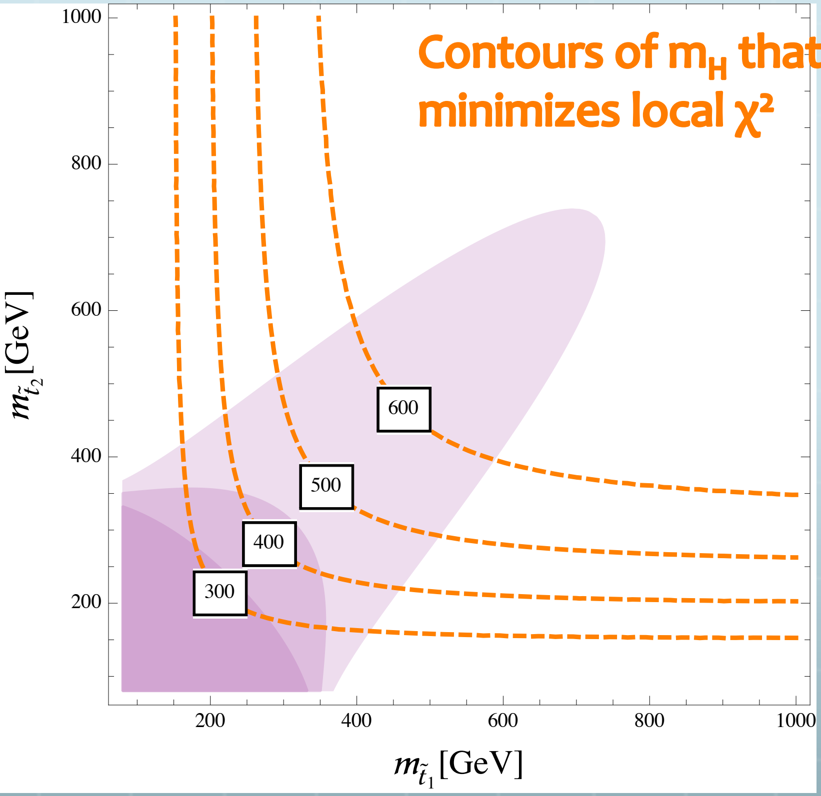
$$r_b \approx \left(1 - \frac{m_h^2}{m_H^2}\right)^{-2},$$

$$\approx 1 \boxed{+} 0.22\left(\frac{400\,\mathrm{GeV}}{m_H}\right)^2$$

Heavy Higgs mass

Blum, D'Agnolo and JF 2012



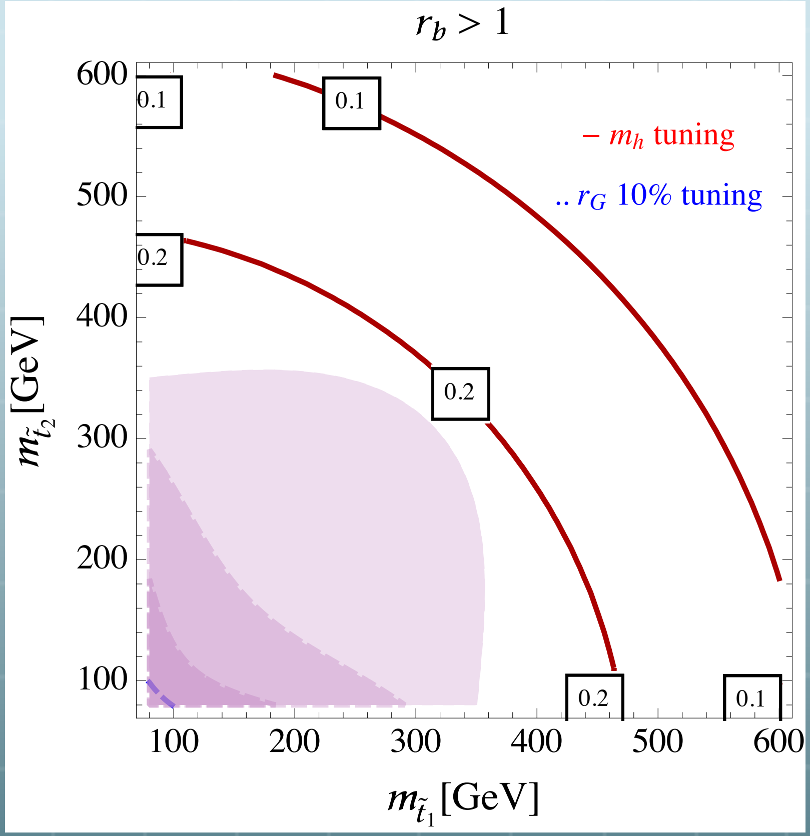


The heavy Higgs has to be light (lighter than 500 GeV) to relax the constraints on stop masses

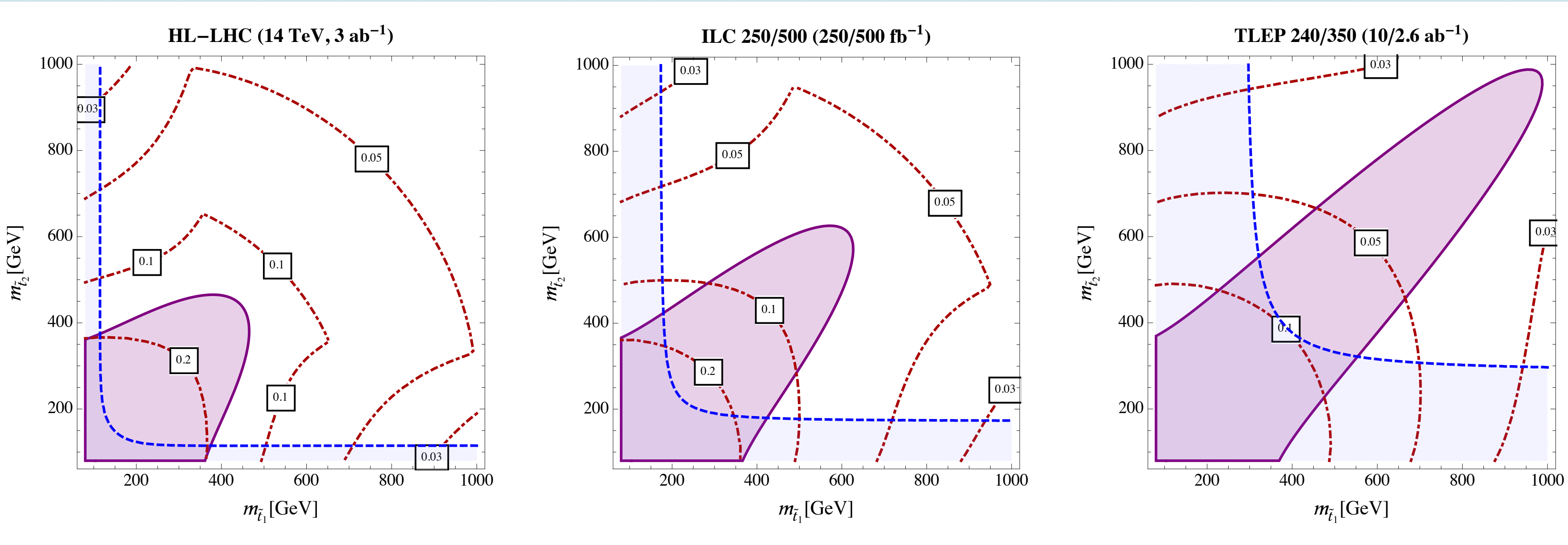
Currently, both ATLAS and CMS perform neutral heavy Higgs search in $A \rightarrow \tau\tau$;
the bound is very sensitive to $\tan\beta$:
at $\tan\beta = 10$, $m_A \sim 300$ GeV

ATLAS also looks for $H \rightarrow WW \rightarrow l\nu l\nu$ and excludes neutral heavy Higgs up to 250 GeV;
It will also be of interest to look for $H \rightarrow ZZ$

The constraint could be relaxed considerably for natural SUSY models with small tan β ~ 1 (such as F-term models) if the bottom Yukawa is enhanced, which is not true in quite a few models which works at small tan β (Dirac NMSSM, λSUSY…)



Prospects for LHC Run 2 and future colliders



Purple shaded: 2 σ excluded regions

Higgs coupling deviations and a new bosonic scale

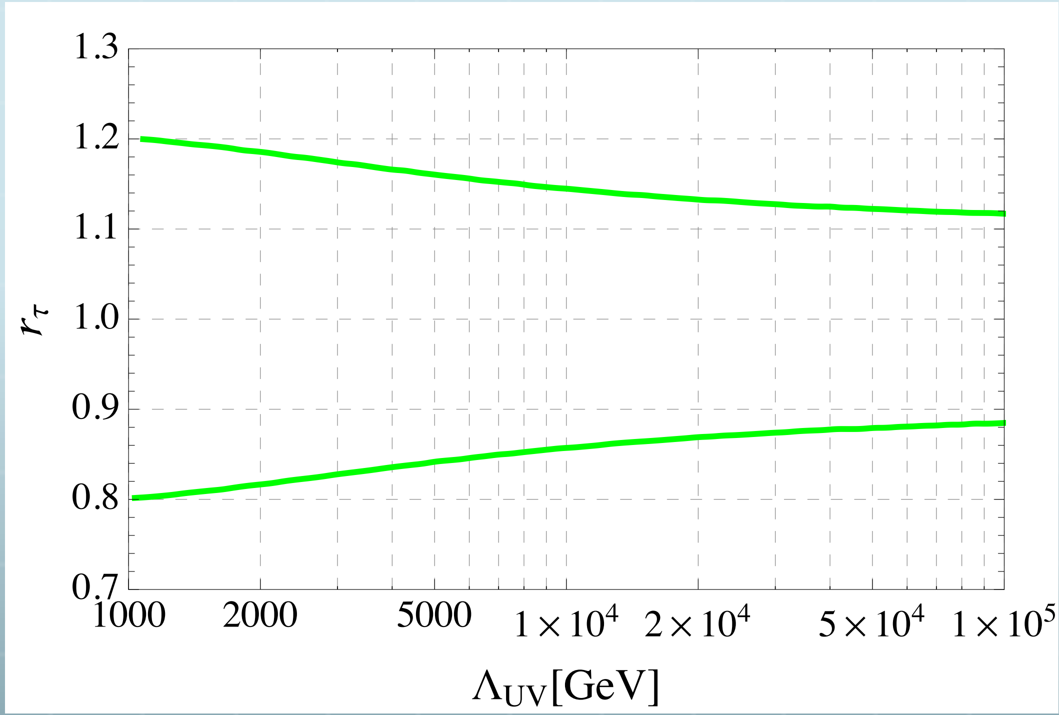
Arkani-Hamed, Blum, D'Agnolo and JF 2012
Blum, D'Agnolo and JF, work in progress

Suppose that we find evidence for deviation in one/more Higgs couplings in the upcoming experiments. Assume that there is no other light scalar (and associated gauge bosons) in the low energy spectrum and the deviations purely come from new fermions beyond the SM which couples to the SM Higgs.

The new Yukawa couplings will push Higgs quartic coupling to large negative values in the UV, triggering an unacceptable vacuum instability at a scale Λ_{uV} .

Beneath $\Lambda_{uV,}$ bosonic degrees of freedom must kick in to rescue vacuum instability.

For example: new vector-like leptons mixing with tau



deviation ~ 10%,
Λ_{uv} ~ 10-100 TeV

Conclusion

- Higgs couplings would be a powerful indirect probe of beyond SM physics!
- Without interplay between different Higgs coupling modifications, both stops lighter than 400 GeV is excluded by Higgs data. The constraints also suggest a minimum electroweak fine-tuning of between a factor of 5 to 10.
- The constraint is independent of how stops decay and is complementary to the direct searches.
- Higgs coupling deviations could tell us the existence of a new bosonic scale beyond the SM!

Thank you!